Strain-sensitivity properties of discontinuous metal films

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Discontinuous thin metal films have been studied for strain gauge applications. A model has been proposed which consists of an array of metal sphere segments. The main criteria in choosing this model is the selection of a suitable metal with a suitable film thickness, which can give a high value of gauge factor as well as a temporal stability. The proposed model has been applied for gold, nickel and platinum films. The maximum value of the gauge factors for these films were found to be approximately equal. This value was around 85, for a film thickness of 45, 65, and 70 °A for gold, nickel and platinum films, respectively. The temperature coefficient of resistance of the gold film was found to be more stable with the film thickness compared to that of nickel and platinum films. This is an advantage as the island thickness may vary with time.

تم دراسة الرقائق المعدنية الغير متصلة لاستخدامها في تطبيقات معيار الضغط. تم عمل نموذج يتكون من قطع معدنية كروية الشكل. إن المعيار الأساسي في اختبار هذا النموذج هو اختيار أنسب معدن وأنسب سمك للرقائق المعدنية لكي يعطينا قيمة عالية لمعامل المعيار. وقيمة عالية للاتزان الوقتي والنموذج المقترح، تم تطبيقه للذهب والنيكل والبلاتين وقد وجد أن أعلى قيمة لمعامل المعيار لهذه الرقائق كانت متقاربة لـ ٨٥ لسمك ٤٥، ٦٥، ٧٥ أنجستروم للذهب والنيكل والبلاتين على التوالي. وقد وجد أن معامل الحرارة – المقاومة. للرقائق الذهب كان أكثر ثباتا مع سمك الطبقة بالمقارنة لرقائق النيكل أو البلاتين. وهذه تعتبر ميزة حيث أن سمك الطبقة يمكن أن يتغير مع الوقت.

Keywords: Gauge factor, Quantum mechanical tunnelling, Temperature coefficient of resistance

1. Introduction

Ultrathin metal films are usually discontinuous ones [1-3] which most probably, consist of submicroscopic metal particles (islands) randomly distributed in a planner mode onto a substrate. Discontinuous Metal Films (DMFs) have interesting and peculiar properties such as the ability to conduct electricity despite the absence of a physical continuity. Different mechanisms have been proposed to account for the electron transfer between the metal islands [4-6]. One of these mechanisms is the quantum mechanical tunnelling [7] of electrons between the islands. DMFs have non-linear I-V characteristics and extremely high gauge factor (~100) [8] compared with those for continuous metallic films (~8) [9]. Nevertheless, the problem of electrical conduction in DMFs is not fully resolved and therefore there is always a need to go further to understand the phenomena. DMFs have Substantial potential to be used as strain gauges [10,11]. Their operation relies upon an electromechanical property, namely, the change in the electrical resistance R of the strain gauge under the influence of a strain ξ [12-14] .The sensitivity of the strain gauge to ξ is determined by the gauge factor γ which is given by:

$$\gamma = \Delta R/R\xi, \tag{1}$$

where ΔR is the change in the resistance R of the strain gauge due to the strain ξ.

The main criteria in choosing a metal for strain gauges are; the large Gauge Factor (GF), low Temperature Coefficient of Resistance (TCR) and excellent thermal and temporal stability.

2. Theoretical analysis

The current density equation at low field $\delta E > 1.0$ eV [4,15] is given by:

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$$J = \frac{g4\pi me\,(\pi BkT)}{h3B2\sin(\pi BkT)} \times$$

$$\exp(-\gamma)\left[\frac{1-\exp\{1-B(\delta E+eV)\}}{1-\exp\{(\delta E+eV)/kT\}} \pm \frac{1-\exp\{\pm B(\delta E-eV)\}}{1-\exp\{(\delta E-eV)/kT\}}\right], \tag{2}$$

where; V is the applied voltage, g is the geometrical factor that takes into account the fact that tunneling occurs across non planner barrier, m* is the effective reduced electron tunneling mass, e is the electron charge, φ is the effective barrier height, s is the inter-island separation, δE is the electrostatic activation energy, k is the Boltzman constant, T is the absolute temperature, h is Plank's constant and B= 2 $\pi/h(2\ m^*/\varphi)^{1/2}$s.

The proposed model is shown in fig. 1, the discontinuous metal film consist of an array of the shown spherical segment evaporated on a glass substrate coated with SiO_2.

According to Parker [16] the quantity $4\pi/h(2\ m^*\varphi)^{1/2}$ s is the gauge factor γ i.e.,

$$\gamma = 4\pi/h(2\ m^*\varphi)^{1/2}\ s. \tag{3}$$

Dividing both sides of eq. (2) by the electric field E we get:

$$\sigma = \frac{g4\pi me(\pi BkT)}{h^3 B^2 \sin(\pi BkT)E} \times \exp(-\gamma)$$

$$\left[\frac{1-\exp\{1-B(\delta E+eV)\}}{1-\exp\{(\delta E+eV)/kT\}} - \frac{1-\exp\{\pm B(\delta E-eV)\}}{1-\exp\{(\delta E-eV)/kT\}}\right]. \tag{4}$$

Abeles conductivity equation [17] in the case of low field $\delta E > eV$ is given by:

$$\sigma = \frac{ge^2}{h(2r+s)} \operatorname{Exp}\left(\frac{\delta E}{kT} - 2Bs\right). \tag{5}$$

Where r is the radius of the spherical segment. Comparing eqs. (4) and (5) we get an expression for the gauge factor γ as;

$$\gamma = \ln\left|\frac{4\pi\, me\,(\pi BkT)}{h^3 B^2 \sin(\pi BkT)E}\right| - \ln\left|\frac{\sigma}{g}\right| +$$

$$\ln\left[\frac{1-\exp\{1-B(\delta E+eV)\}}{1-\exp\{(\delta E+eV)/kT\}} - \frac{1-\exp\{-B(\delta E-eV)\}}{1-\exp\{(\delta E-eV)/kT\}}\right]. \tag{6}$$

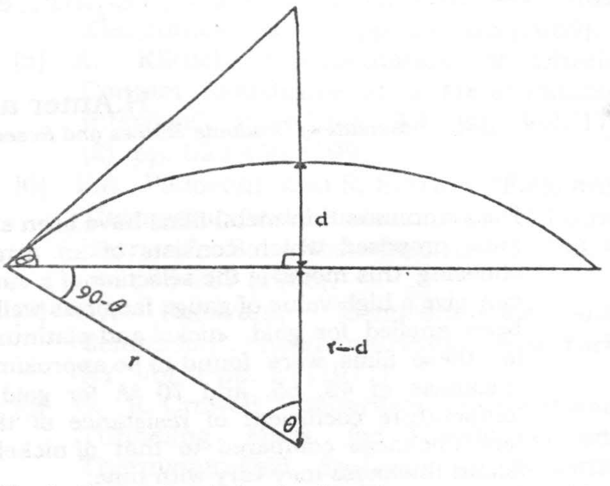

Fig. 1. Geometric relation for the sphere segment model.

The following relations are related to the proposed model.

a) The volume of the spherical segment shown in fig. 1 is given by :

$$V = \frac{1}{3}\pi R^3 (1-\cos\theta)^2 (2+\cos\theta). \tag{7}$$

b) The surface area A of the spherical segment is given by:

$$A = 2\pi R^2 (1-\cos\theta), \tag{8}$$

where θ is the contact angle.

c) The electrostatic activation energy: from the definition of the electric field strength E=D/ε where ε is the dielectric constant and D is the surface charge is given by:

$$D = \frac{e}{2\pi R^2 (1-\cos\theta)}, \tag{9}$$

$$E = \frac{e}{2\pi\varepsilon R^2 (1-\cos\theta)}. \tag{10}$$

The electrostatic activation energy is given by [13]:

$$\delta E \approx \frac{1}{2}\int \varepsilon E^2 dV. \tag{11}$$

Therefore δE in our model is given by:

$$\delta E = \frac{3}{2}\int_{0}^{0}\int_{0}^{2\pi}\int_{R}^{R+S}\frac{e^2}{8\pi^2\varepsilon R^4}\frac{\sin\theta\,(1-\cos^2\theta)}{(1-\cos\theta)^2}\,d\theta\ \ d\phi\ \ dR$$

$$= \frac{3e^2}{16\pi\varepsilon r}\left\{(2\theta+\sin\theta(4+\cos\theta)\left(\frac{S}{r+S}\right)\right\}. \qquad (12)$$

By adding the effect of the thermal expansions of both the metal film α_m and the substrate α_s, the electrostatic activation energy will be given by [11]

$$\delta E = \frac{3e^2}{16\pi\varepsilon}\{2\theta+\sin\theta(4+\cos\theta)\}$$

$$\left[\frac{1}{r(1+\alpha_m T} - \frac{1}{(S+r)(1+\alpha_s T)}\right]. \qquad (13)$$

d) The voltage drop V across the tunneling gap is given by:

$$V = \int E.dl = \int_{r}^{r+s}\frac{e}{2\pi r^2}\frac{\sin\theta}{(1-\cos\theta)}\,dr = \frac{e}{2\pi\varepsilon}\left(\frac{1}{2r+s}\right). \qquad (14)$$

The average overall electric field intensity is given by:

$$E = \frac{e}{2\pi r\varepsilon}\left(\frac{S}{r+s}\right)\left(\frac{1}{2r+s}\right). \qquad (15)$$

e) Evaluation of the contact angle θ of the metal island. From the geometric relation of fig.1 we get:

$$\frac{r}{d} = \frac{\sin\theta}{1-\cos\theta} = \left(\frac{1+\cos\theta}{1-\cos\theta}\right)^{1/2}. \qquad (16)$$

Where d is the thickness of the metal island.

Putting $F = \left(\frac{r}{d}\right)^2$,

θ is found from eq. (16) to be expressed as:

$$\theta = \cos^{-1}\left(\frac{F-1}{F+1}\right). \qquad (17)$$

The r/d values can be determined from the experimental data of Kazmerski [18] for thin gold films. The empirical formula obtained from such data takes the form;

$$\theta_1 = -\,2\times10^{-5}\,(d\times10^{10})^2 + 0.0105\,(d\times10^{10}) + 0.3286. \qquad (18)$$

A general relation for a contact angle θ_2 assuming that the different type of metal islands are composed of the same number of molecules and have the same arrangements of atoms is obtained:

$$\theta_2 = 2\times10^{-5}\left(d_2\times10^{10}\frac{y_1}{y_2}\right)^2\left(d_2\times10^{10}\frac{y_1}{y_2}\right)+0.3286. \qquad (19)$$

Where; d_1, y_1, θ_1, are the thickness, atomic radius and contact angle of the gold island respectively, and d_2 and y_2 are the thickness and the atomic radius of the metal island of contact angle θ_2.

f) The effective potential barrier ϕ is equal to the difference between the substrate electron affinity χ and the metal work function ψ [15] i.e.,

$$\varphi = \left[\psi - \left(\frac{eE}{4\pi\varepsilon}\right)^{0.5} - \chi_s\right], \qquad (20)$$

and $\left(\frac{eE}{4\pi\varepsilon}\right)^{0.5}$ is the effect of the image force.

Where, $\chi = 1$eV for glass substrate (our case)

g) The relative effective dielectric constant

According to Morris [15] the relative effective dielectric constant is approximately equal to:

$$\frac{\varepsilon_r(1+2\chi)}{(1-\chi)}, \qquad (21)$$

where x is the volume fraction of the metal island and for our model is given by:

$$x = \frac{\pi r^3\,(1-\cos\theta)^2\,(2+\cos\theta)}{3\,(2r+s)^2\,d.\sin^3\theta}. \qquad (22)$$

h) The inter-island separation s. From the experimental data of Kazmerski and Diane [17] which shows the dependence of the island radius r and the inter-island separation s on the thickness of gold films. We get the following empirical relation,

$$s = 0.1642 \times (\theta)^{-2.7022} \times r. \quad (23)$$

This relation could be generalized by substituting the respective values of the contact angle θ_2

3. Results and discussion

The commercial software MCAD version 7 has been used to calculate the variable parameters in this study. According to the condition of the low field regime KT > eV [18] there is a critical value for the film thickness below which the conductivity lies in the high field regime. The temperature coefficient of resistance TCR is given by [19]:

$$TCR = -(1/\sigma).d\sigma/dT = -d\ln\sigma/dT,$$

$$=[4\pi/h(2m^*\varphi)^{1/2}(\Delta s/\Delta T)]-E/kT, \quad (24)$$

where,

$\Delta s=\alpha_s.\ s.\Delta T.$

Thus depending on the predominance of one of the two opposing terms above in eq. (24), we expect to observe a positive or a negative TCR of varying magnitudes. It is to be noticed that the gauge factor varies with the temperature. Fig. 2 shows the variation of the gauge factor with the films thickness, where for gold films, the gauge factor decreases form 85 to 23 for a film thickness increase in the range between 48 and 170°A. For nickel films, the gauge factor decreases from 85 to 50, for a film thickness increase of 60 to 140 ° A , then it rises again with the increase of the film thickness. For a thickness of 170 °A we have a gauge factor of 55, this is due to the mobility coalescence [20, 21, 22]. Coalescence is the ability of the islands to move, collide and then combine with one another. The mobility of an island depends on its metal type and size, the smaller islands are the fastest. For platinum films, the gauge factor decreases from 87 to 46 for a film thickness increase of 70 to 160 °A.

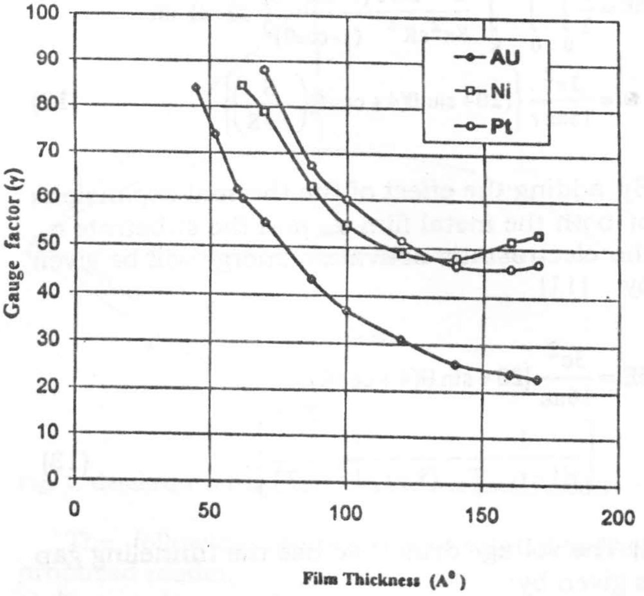

Fig. 2. The gauge factor of discontinuous Au, Ni and Pt films as a function of the film thickness at T = 293 K.

We notice from fig. 2 that each metal has a threshold film thickness below which there is no gauge factor, i.e. no activation energy. The threshold film thickness is equal to 48, 60, 70 for gold, nickel and platinum films, respectively.

Fig. 3 shows the variation of the gauge factor γ with the inter-island separation s (barrier thickness) for gold, nickel and platinum films. This is a linear relation according to eq.(3). The gauge factor γ_o is the gauge factor of the previous model [16].

Fig. 4 shows the variation of the activation energy δE with inter-island separation s (barrier thickness). This is also a linear relation i.e. as s increases δE increases, and when s tends to zero δE vanishes.

From fig. 2 we can notice that gold films have a lower gauge factor than nickel, and platinum films. From fig. 5, considering values for film thickness just above the threshold value of the film thickness, gold films are more stable than platinum and nickel films as its TCR value is nearly zero i.e. more stable gauge factor [11]. This is an advantage for gold films, i.e. they are more sensitive than nickel and platinum films, as the main problem of tunnelling thin film strain gauges lies in stability with time, presumably due to island coalescence.

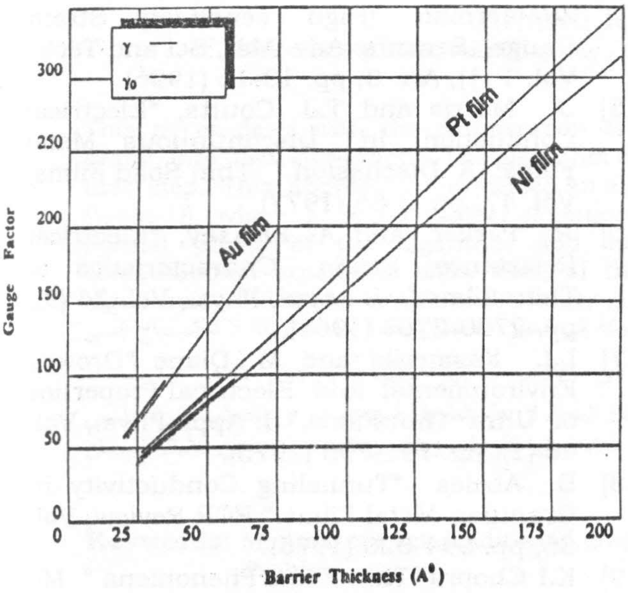

Fig. 3. The gauge factor of discontinuous Au, Ni and Pt films as a function of the barrier thickness at T = 293 K.

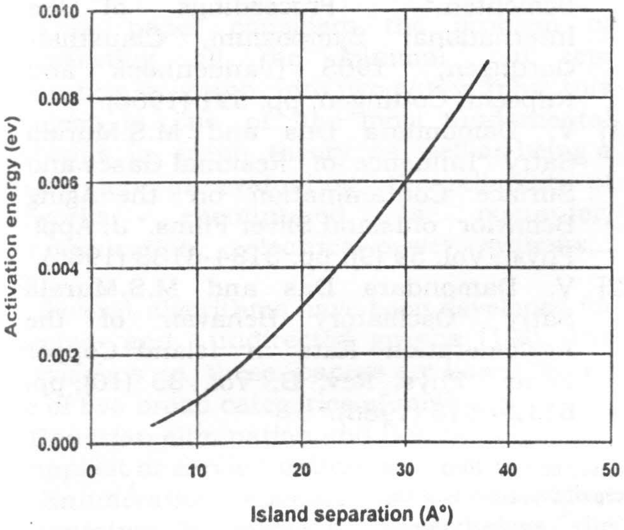

Fig. 4. Variation of the activation energy δE with the inter-island separation s.

4. Conclusions

The proposed model has some advantages over the previous one, [16] such as:

1. The effect of the activation energy, temperature, film thickness, and inter-island separation on the gauge factor are more clear, i.e. their range of effectiveness could be detected and therefore analysed.
2. The present model has defined an inter-island separation s for which tunnelling can occur. This is in the range of 10-38 °A for gold films, 26-60 °A for nickel films, and 29-58 °A for platinum films, fig. 3, but the previous model [16] proposed an inter-island separation of 100 °A for this inter-island separation no activation energy can occur.
3. Knowing the variation of TCR with the film thickness we can select a metal for which the effect of temperature on it is weak such as gold in the present work.

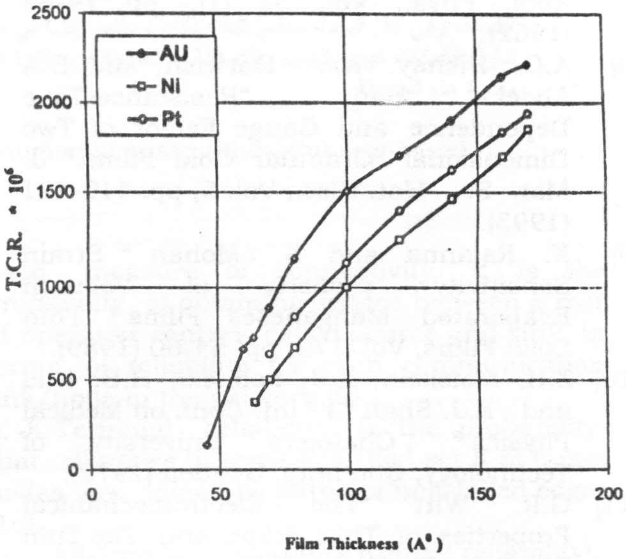

Fig. 5. Variation of TCR of discontinuous Au, Ni and Pt films with film thickness at T = 293 K.

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